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04 Respiration in plants

1. Introduction :

- The **breaking of C – C single bond of complex compounds** through oxidation within the cells, leading to release of considerable amount of energy and the trapping of this energy for **synthesis of ATP** is called **cellular respiration**.

Photosynthesis ⟶ **Sugar synthesis** ($C_6H_{12}O_6$) ⟶ **Breaking C–C bonds or oxidation** ⟶ **ATP Synthesis** ↓ **Cellular respiration**

- During cellular respiration or oxidation within a cell, all the **energy** contained in compounds is **not released in a single step** because in single if the complete energy is released it may be converted into heat. So the energy during cellular respiration is released in a series of slow step wise reactions controlled by enzymes and it is trapped as chemical energy in the form of ATP.
- ATP thus synthesised, is broken down whenever and wherever energy needs to be utilised, hence **ATP act as the energy currency of the cell**.
- The compounds that are oxidised during the process of cellular respiration are called respiratory substrates, these are usually carbohydrates but except these fats, **proteins & organic** acids can also be used as respiratory substrates.
- **Primarily carbohydrates (mainly glucose)** are used as respiratory substrate. In the absence or less availability of carbohydrates, the respiratory substrates can be **fats & proteins**.

Respiratory substrate	Gross Calorific value	Physiological value
Carbohydrate	4.1 kcal/g	4.0 kcal/g
Protein	5.65 kcal/g	4.0 kcal/g
Fat	9.45 kcal/g	9.0 kcal/g

- The sequence of use of respiratory substrates –
  (i) Carbohydrate (ii) Fat (iii) Protein
- **Organic acids such as malic acid etc. can be used as respiratory substrates in some plants, under certain conditions**.

Features of Cellular respiration:

(i) Cellular respiration is an **amphibolic process**.
Reason: The carbon skeleton (Intermediates of respiration) produced during respiration is used as precursors for biosynthesis of other molecules in the cell.

(ii) Cellular respiration is an **exergonic process**.
Reason: The breaking of C–C bonds of complex compounds through oxidation within the cells, leading to release of considerable amount of energy.

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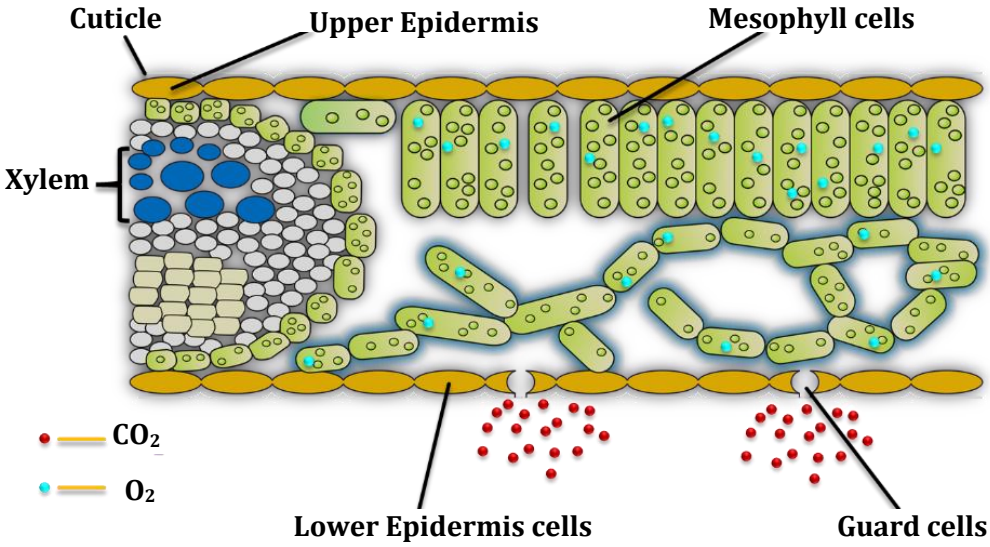
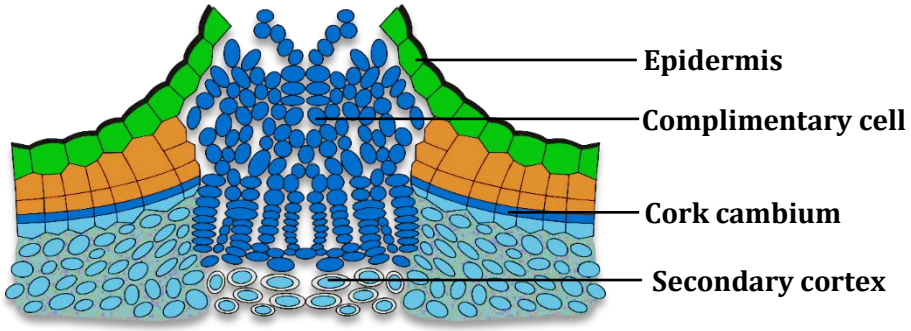
2. Do Plants Breathe?

- **Plants, unlike animals, have no specialised organs for gaseous exchange** but they have stomata and lenticels for this purpose.



- There are several **reasons why plants can get along without respiratory organs**.
- First, each plant part takes care of its own gas-exchange needs. There is very little transport of gases from one plant part to another.
- **Second, plants do not present great demands for gas exchange**. Roots, stems and leaves respire at rates far lower than animals do. Only during photosynthesis are large volumes of gases exchanged and, each leaf is well adapted to take care of its own needs during these periods. When cells photosynthesis, availability of O_2 is not a problem in these cells since O_2 is released within the cell.
- **Third, the distance that gases must diffuse even in large, bulky plants is not great**. Each living cell in a plant is located quite close to the surface of the plant. In stems, the 'living' cells are organised in thin layers inside and beneath the bark. They also have openings called lenticels. The cells in the interior are dead and provide only mechanical support. Thus, most cells of a plant have at least a part of their surface in contact with air. This is also facilitated by the loose packing of parenchyma cells in leaves, stems and roots, which provide an interconnected network of air spaces.



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3. Types of Respiration :

(A) On The Basis Of Type Of Respiratory Substrates:

(1) Floating respiration: - When carbohydrate or fats are oxidised inside the cell. Carbohydrates and fats are floating inclusions of cell thus, this is called floating respirations.

(2) Protoplasmic respiration: - When protein is oxidised inside the cell. This occurs in starved cell. Protein is constituent of protoplasm thus, this is called protoplasmic respiration.

(B) On The Basis of Presence or Absence of O_2 :

(1) Aerobic

(2) Anaerobic/Fermentation

Aerobic		Anaerobic/Fermentation	
1.	This accounts for complete oxidation (end products are inorganic) of food (glucose) to CO_2 and H_2O	**1.**	This accounts for only a partial breakdown of glucose to either lactic acid or ethanol and CO_2
2.	Its an intermolecular respiration	**2.**	It's an intramolecular respiration.
3.	36 or 38 molecules of ATP gain for each molecule of glucose.	**3.**	There is gain of only two molecules of ATP for each molecule of glucose.
4.	NADH is oxidised to NAD^+ vigorously.	**4.**	NADH is oxidised to NAD^+ rather slowly.
5.	O_2 remove hydrogen from the system and acts as the final hydrogen acceptor.	**5.**	O_2 is absent. Hydrogen acceptor in the system is either acetaldehyde (during alcoholic fermentation) or pyruvate (during lactic acid fermentation)
6.	**Reaction** $C_6H_{12}O_6+6O_2+6H_2O \rightarrow 6CO_2+12H_2O+686$ Kcal	**6.**	**Reaction** $C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH+2CO_2$+ less than 7% of energy of glucose 'or' $C_6H_{12}O_6 \rightarrow 2C_3H_6O_3$+ less than 7% of energy of glucose

4. Mechanism of Cellular Respiration :

(A) Glycolysis/Emp (Embden, Meyerhof, Parnas) Pathway :

i. The term glycolysis has originated from the Greek words glycos for sugar, lysis means splitting. The scheme of glycolysis was given by Gustav Embden, Otto Meyerhof & J. Parnas so glycolysis is often called EMP pathway.

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ii. In all living organisms whether it is aerobic or anaerobic, the first step in cellular respiration is partial breakdown or oxidation of glucose into two molecules of pyruvic acid and it is called glycolysis.

iii. The glycolysis is common phase between aerobic & anaerobic respiration. In anaerobic organisms, it is the only process in respiration.

iv. In plants the glucose is derived from sucrose (product of photosynthesis) or from starch (storage carbohydrate).

v. Sucrose is converted into glucose and fructose by the enzyme invertase and these two monosaccharides enter the glycolytic pathway.

vi Glycolysis occurs in the cytoplasm of the cell, this process is independent of oxygen, it means it can occur in both conditions, presence of O_2 or absence of O_2.

vii. It involves a series of ten biochemical enzymatic reactions in cytoplasm.

viii. Glucose and fructose are phosphorylated to give rise to glucose-6-phosphate and fructose-6-phosphate respectively by the activity of the enzyme hexokinase. This phosphorylated form of glucose then isomerises to produce fructose-6-phosphate. Subsequent steps of metabolism of glucose and fructose are same.

ix. In glycolysis, a chain of ten reactions, under the control of different enzymes, takes place to produce pyruvate from glucose.

- In Glycolysis, no consumption of oxygen & no liberation of CO_2 takes place.
- In glycolysis, 1 glucose (6C), break down into 2mol. of pyruvic acid (3C) (Partial oxidation).
- Pyruvic acid is the key product of glycolysis.
    - 2 $NADH_2$, produced during the process enter into ETS (In mitochondria) to produce 4ATP (if glycerol phosphate shuttle is present) or 6ATP (if malate aspartate shuttle is present), this ATP formation is called oxidative phosphorylation.
    - Substrate level phosphorylation [When the substrate releases energy for phosphorylation of ADP (formation of ATP) without ETS then this method of ATP formation is called as substrate level phosphorylation], forms 4 ATP, 2ATP consumed, so 2ATP gained by SLP. (Direct gain)

Control of Glycolysis :

- In glycolysis first, third and last step are irreversible, these are control points of glycolysis, where process can be controlled, if required.
- Step third is the most important control point of glycolysis, this step is regulated by an allosteric enzyme phosphofructokinase. This enzyme is allosterically activated by AMP and allosterically inhibited by ATP. This enzyme is called pacemaker enzyme of glycolysis.

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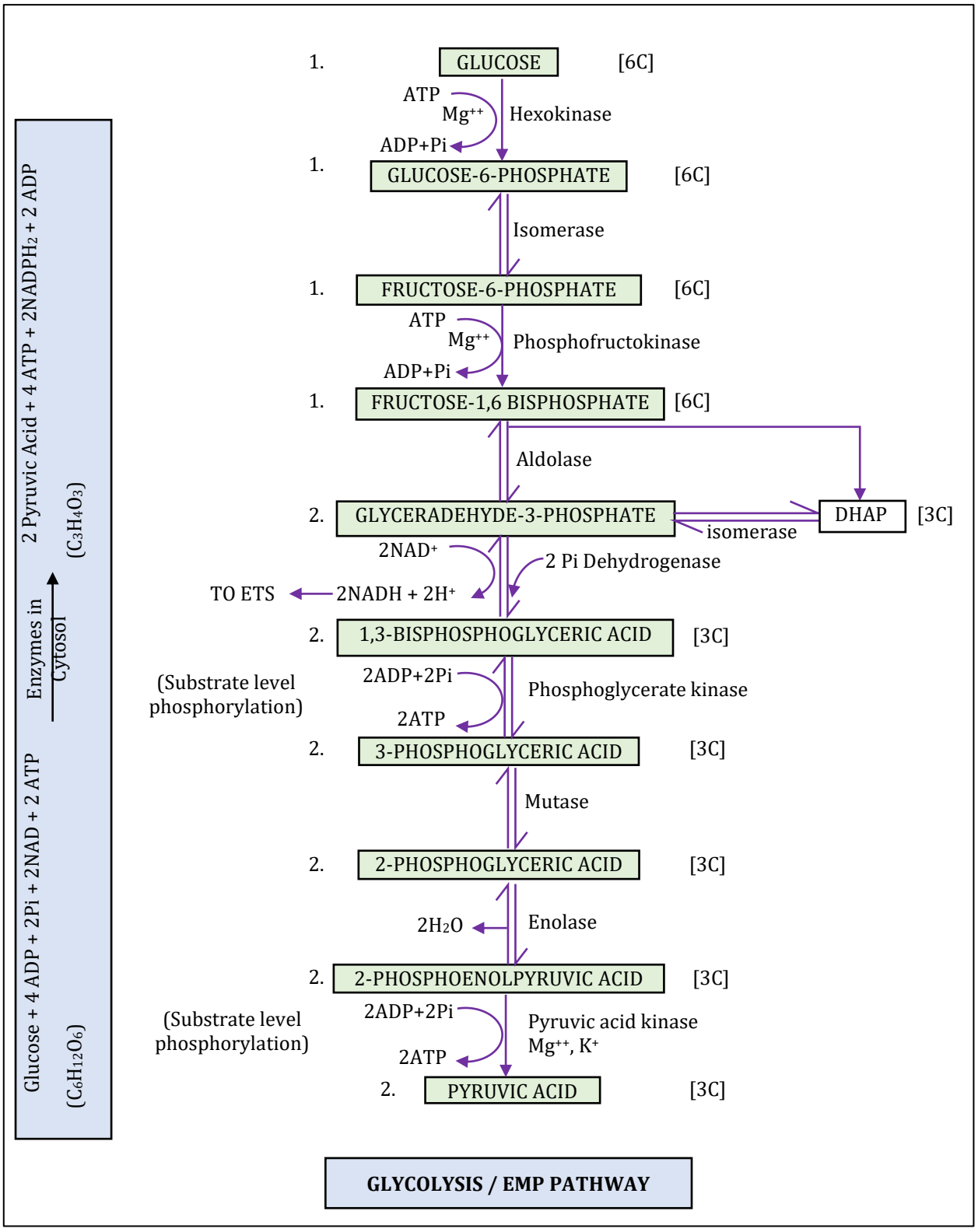

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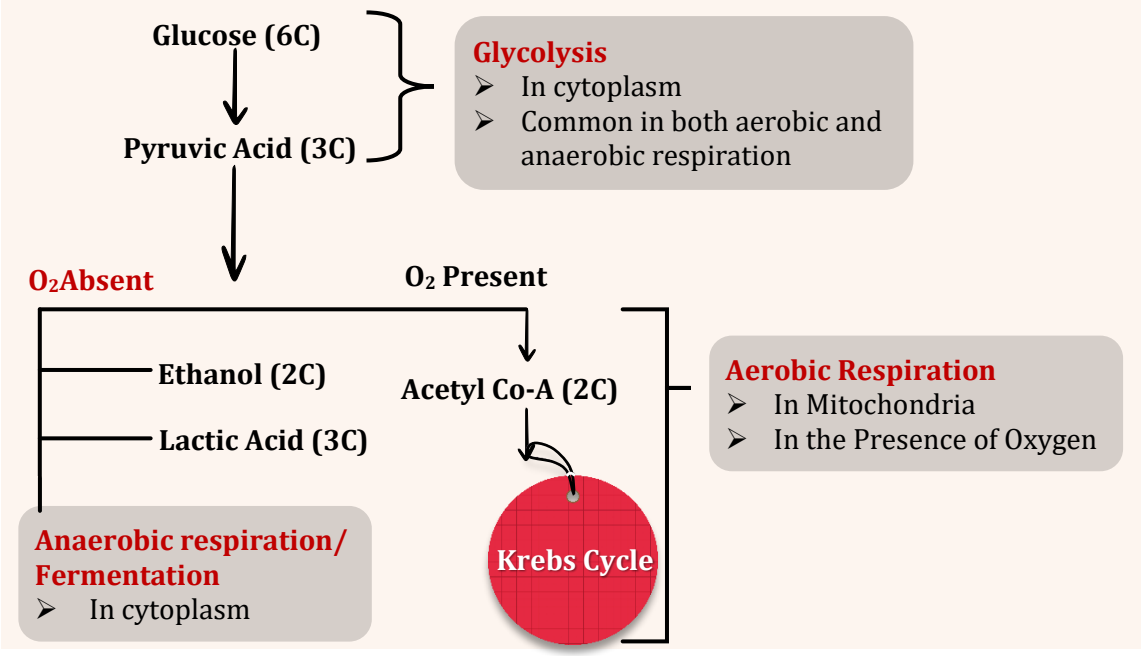
Fate of Pyruvic Acid :



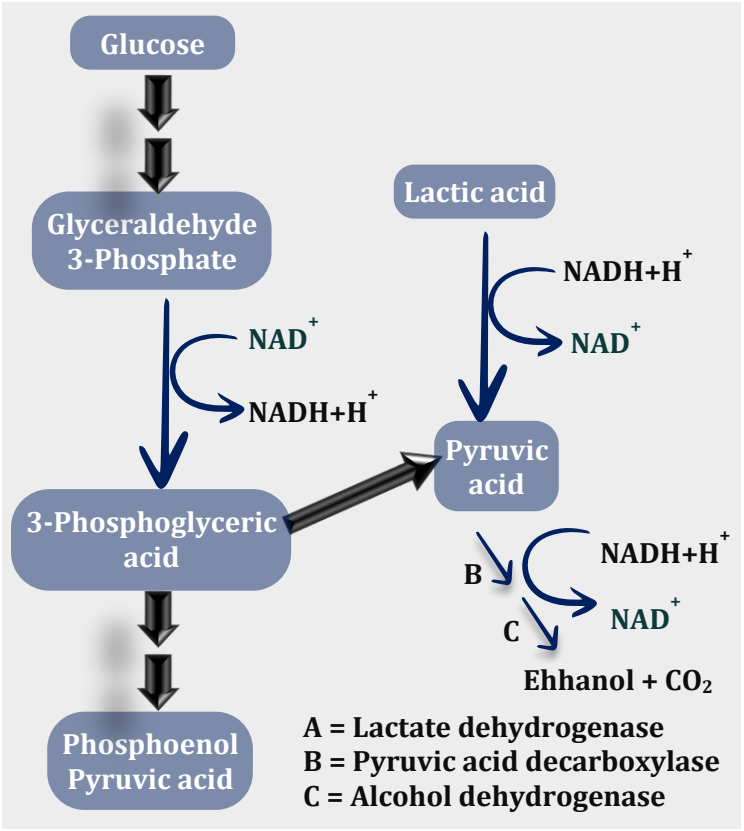
(B) Anaerobic Respiration of Fermentation :

- Fermentation takes place under anaerobic conditions in many prokaryotes, unicellular eukaryotes and in germinating seeds.

Examples of anaerobic respiration or fermentation:

1. **Lactic acid anaerobic respiration:** In human muscles (during exercise when oxygen is inadequate).
2. **Alcoholic fermentation:** In yeast.

- Alcoholic fermentation is used in the formation of beverages (alcoholic drinks) and Bread.
- Bread become puffed or spongy due to release of CO_2 during the process.
- In both lactic acid and alcohol fermentation not, much energy is released; less than seven per cent of the energy in glucose is released and not all of it is trapped as high energy bonds of ATP.
- Also, the processes are hazardous – either acid or alcohol is produced. Yeasts poison themselves to death when the concentration of alcohol reaches about 13 per cent.



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- In Anaerobic respiration or fermentation, the net gain of ATP is 2 ATP because during the process, in glycolysis, 4 ATP are synthesised by the substrate level phosphorylation and 2 ATP are consumed, so – net gain = 4 – 2 = 2 ATP (The 2NADH + H+ produced during glycolysis do not enter into ETS, instead they are utilised to form alcohol or lactic acid).
- Lactic acid fermentation is also performed by bacteria Lactobacillus. It is used in curd and other dairy products formation. Curd become sour due to excess lactic acid fermentation.
- In aerobic respiration, there is an external final electron acceptor i.e. O_2 while in fermentation, there is no external electron acceptor. The final electron acceptor is organic intermediate of the process.

Pasteur effect:

It is an inhibitory effect of oxygen on the fermentation process.

Explanation:

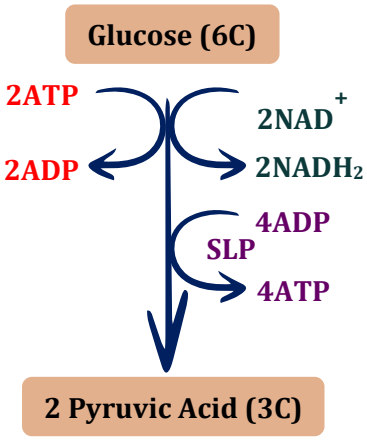
- The effect can be easily explained; as the yeast being facultative anaerobes can produce energy using two different metabolic pathways.

(i) While the oxygen concentration is low, the product of glycolysis, pyruvate is turned into ethanol and CO_2 and the energy production efficiency is low (2 moles of ATP per mole of glucose).

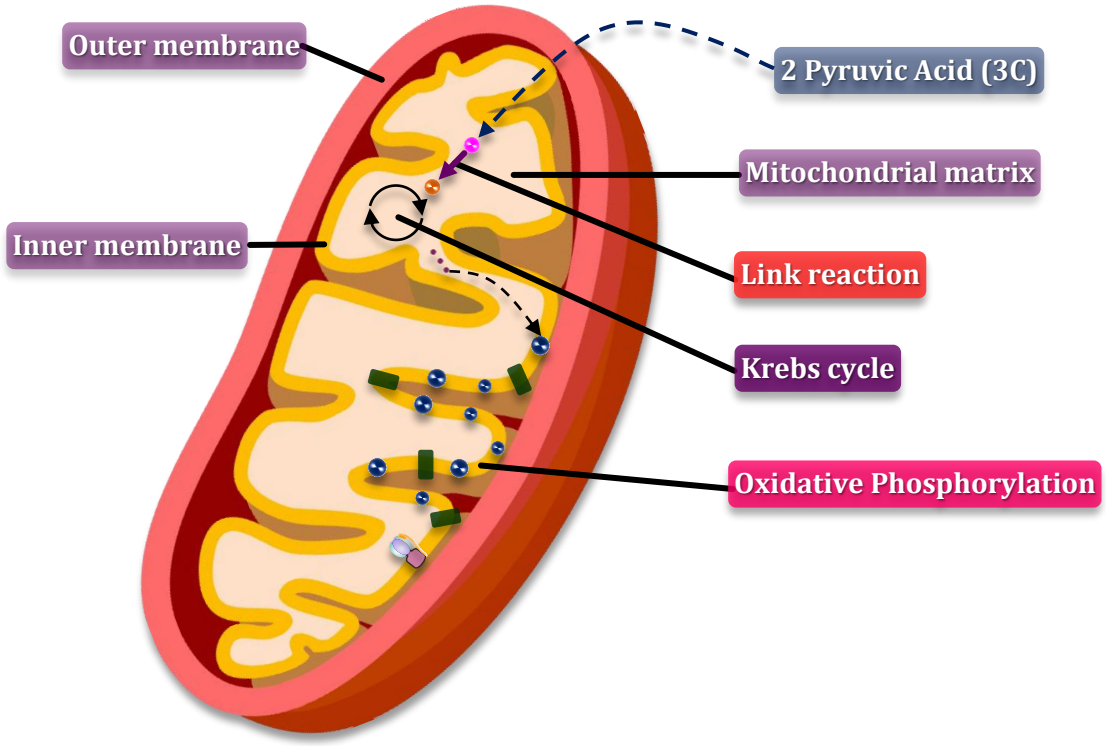
(ii) If the oxygen concentration grows, pyruvate is converted into acetyl CoA that can be used in the citric acid cycle, which increases the efficiency to 36 moles of ATP per mole of glucose.

5. Aerobic Respiration :

- For aerobic respiration to take place within the mitochondria, the final product of glycolysis, pyruvate is transported from the cytoplasm into the mitochondria. The crucial events in aerobic respiration are:
- The complete oxidation of pyruvate by the stepwise removal of all the hydrogen atoms, leaving three molecules of CO_2. (Link reaction and Krebs cycle)
- The passing on of the electrons removed as part of the hydrogen atoms to molecular O_2 with simultaneous synthesis of ATP. (ETS and Oxidative phosphorylation)



What is interesting to note is that the first process takes place in the matrix of the mitochondria while the second process is located on the inner membrane of the mitochondria.



(A) Link/Gateway Reaction (Formation of Acetyl-Co-A) :

i. This process connects Glycolysis and Krebs cycle so it is called Link reaction or Gateway reaction. During this process 1st time CO_2 is evolved during respiration.

ii. Acetyl Co-A is a connecting link between glycolysis & Krebs -cycle. Decarboxylation and dehydrogenation (Oxidative decarboxylation) takes place during formation of acetyl Co-A.

iii. Acetyl Co-A is formed in the matrix by enzyme pyruvate dehydrogenase complex.

iv. This reaction require five cofactors. (Mg^{2+}, LA (Lipoic Acid), TPP (Thiamine pyrophosphate), NAD^+, CoA)

$$\text{Pyruvic acid} + \text{CoA} + NAD^+ \xrightarrow[\text{Pyruvate dehydrogenase}]{Mg^{2+}} \text{Acetyl CoA} + CO_2 + NADH + H^+$$

(B) Krebs Cycle/TCA (Tricarboxylic Acid) Cycle/C_6 (Citric Acid) Cycle :

i. This cycle was discovered by **H. A. Krebs.** (Nobel prize)

ii. TCA cycle occurs in **mitochondrial matrix**. All the enzymes of TCA cycle, except Succinate dehydrogenase (in the inner mitochondrial membrane) present in matrix.

iii. During **Kreb's cycle acetyl CoA** is completely oxidised into CO_2.

iv. Krebs cycle is also called **Citric acid (CA) cycle** because Ist Compound is Citric acid (6C). In this acid, 3 **carboxylic groups** (COOH) are found so process is also called **TCA (Tricarboxylic Acid) cycle.**

v. In Kreb's cycle oxaloacetic acid (OAA) is the first member and it also act as first acceptor of Acetyl Co-A. In the end of this cycle OAA re-formed.

vi. The TCA cycle starts with the condensation of acetyl group with oxaloacetic acid (OAA) and water to yield citric acid. The reaction is catalysed by the enzyme citrate synthase and a molecule of CoA is released.

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vii. Citrate is then isomerised to isocitrate. It is followed by two successive steps of decarboxylation, leading to the formation of a-ketoglutaric acid and then succinyl-CoA.

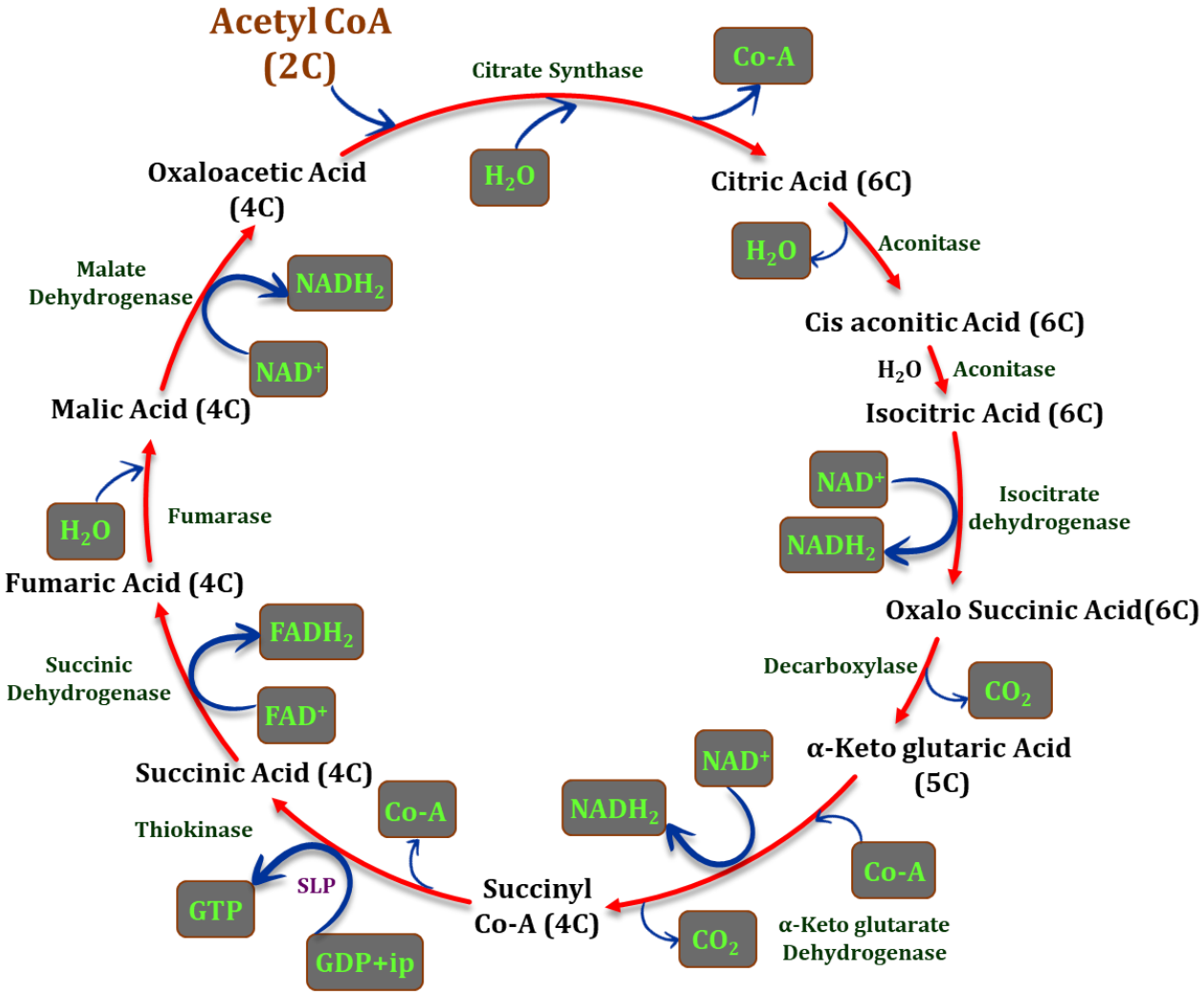
viii. In the remaining steps of citric acid cycle, succinyl-CoA is oxidised to OAA allowing the cycle to continue. During the conversion of succinyl-CoA to succinic acid a molecule of GTP is synthesised. This is a substrate level phosphorylation. In a coupled reaction GTP is converted to GDP with the simultaneous synthesis of ATP from ADP.

ix. Also, there are three points in the cycle where NAD^+ is reduced to NADH + H^+ and one point where FAD+ is reduced to $FADH_2$.

x. The continued oxidation of Acetyl CoA via the TCA cycle requires the continued replenishment of oxaloacetic acid, the first member of the cycle. In addition, it also requires regeneration of NAD^+ and FAD^+ from NADH and $FADH_2$ respectively.

xi. Oxidation or dehydrogenation occurs at 4 places in one Krebs cycle, results in the formation of 3NADH, 1$FADH_2$. Along with 1 GTP (ATP) produced by substrate level phosphorylation in each turn of TCA cycle. (=12 ATP)

xii. Link reaction and Kreb's cycle occurs two times during complete oxidation of 1 hexose molecule because by glycolysis one hexose converts into two pyruvic acid and both the molecules undergo separate link reaction and Krebs cycle.



Golden Key Points

- **ATP act as the energy currency of the cell.**
- **Plants, unlike animals, have no specialised organs for gaseous exchange** but they have stomata and lenticels for this purpose.
- **Step third is the most important control point of glycolysis,** this step is regulated by an **allosteric enzyme phophofructokinase.**
- The **fate of pyruvic acid depends on the availability of oxygen and cellular need.**
- The complete oxidation of pyruvate by the stepwise removal of all the hydrogen atoms, leaving three molecules of CO_2. (Link reaction and Krebs cycle)
- **Acetyl Co-A is formed from pyruvic acid in the matrix by enzyme pyruvate dehydrogenase complex.**
- **All the enzymes of TCA cycle, except Succinate dehydrogenase (in the inner mitochondrial membrane) present in matrix.**
- There are three points in the Krebs cycle where NAD^+ is reduced to NADH + H^+ and one point where FAD^+ is reduced to $FADH_2$.

BEGINNER'S BOX-1

INTRODUCTION, DO PLANTS BREATH?, TYPES OF RESPIRATION, GLYCOLYSIS, AEROBIC RESPIRATION, (LINK REACTION AND TCA CYCLE)

1. Match Column-I with Column-II and select the correct option from the codes given below.

	Column-I		**Column-II**
A.	Glycolysis	(i)	Inner mitochondrial membrane
B.	TCA cycle	(ii)	Mitochondrial matrix
C.	ETS	(iii)	Cytoplasm

(1) A-(iii), B-(i), C-(ii) (2) A-(iii), B-(ii), C-(i)
(3) A-(i), B-(ii), C-(iii) (4) A-(ii), B-(i), C-(iii)

2. The 4-C acid in Krebs cycle is :-
(1) α-ketoglutaric acid (2) citric acid
(3) OAA (4) acetyl coenzyme A

3. Which step is called gateway step/link reaction in aerobic respiration?
(1) Glycolysis (2) Formation of acetyl coenzyme A
(3) Citric acid formation (4) Formation of isocitric acid

4. Which of the following steps is associated with ATP formation (substrate level phosphorylation)?
(1) Succinyl CoA $\rightarrow$ Succinic acid (2) 1, 3 diPGA $\rightarrow$ 3 PGA
(3) PEP $\rightarrow$ Pyruvate (4) All of these

5. Select the correct statement :-
(1) When ATP is synthesized directly from metabolites, it is substrate level phosphorylation
(2) In Krebs' cycle, acetyl-Co-A undergoes 2 decarboxylations and 4 dehydrogenations.
(3) Respiration is an amphibolic process.
(4) All of these

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6. During cellular respiration, the energy is released in : -
(1) Single step (2) Two steps (3) Ten steps (4) Multi steps

7. Which of the following acts as energy currency of cell?
(1) $NADPH_2$ (2) $FADH_2$ (3) ATP (4) Co-Q

8. Find out the correct sequence of use of respiratory substrates?
(1) Protein → Carbohydrate → Fat
(2) Carbohydrate → Fat → Protein
(3) Fat → Carbohydrate → Protein
(4) Carbohydrate → Protein → Fat

9. Which organs are present in plants for gaseous exchange?
(1) Stomata (2) Lenticels
(3) Both 1 and 2 (4) Mesophyll cells

10. On the basis of respiratory substances, types of respiration are-
(1) Floating respiration (2) Aerobic respiration
(3) Protoplasmic respiration (4) Both (1) and (3)

11. What is the final product of glycolysis?
(1) Phosphoglyceraldehyde (2) Phosphoglyceric acid
(3) Phosphoenolpyruvate (4) Pyruvate

12. Which enzyme is known as pacemaker enzyme of glycolysis?
(1) Hexokinase (2) Phosphoglycerate kinase
(3) Phosphofructokinase (4) Pyruvic acid kinase

13. Which of the following process converts sugars into alcohol?
(1) Oxidation (2) Pasteurization (3) Bleaching (4) Fermentation

14. Where does fermentation takes place?
(1) Mitochondria (2) Vacuole (3) Ribosomes (4) Cytoplasm

15. In alcoholic fermentation, the NADH reduces the pyruvate into: -
(1) Lactic acid (2) Hydrogen atom (3) Ethanol (4) Acetyl CoA

16. Yeast poison themselves to death when the alcohol reaches about: -
(1) 10% (2) 12% (3) 13% (4) 14%

17. Tricarboxylic acid cycle was discovered by: -
(1) Hatch and Slack (2) Melvin Calvin
(3) H. A. Krebs (4) Dixon and Jolly

18. 5-Carbon compound present in Kreb's cycle is: -
(1) α-ketoglutarate (2) Iso-citrate
(3) Fumarate (4) Oxalosuccinate

19. $FADH_2$ is formed in Krebs cycle during the formation of: -
(1) Succinyl CoA → Succinate (2) α-ketoglutarate → succinyl CoA
(3) Isocitrare → oxalosuccinate (4) Succinate → fumarate

20. How many NADH and $FADH_2$ are formed during one Krebs cycle?
(1) 2 NADH & 2 $FADH_2$ (2) 3 NADH & 1 $FADH_2$
(3) 1 NADH & 3 $FADH_2$ (4) 3 NADH & 2 $FADH_2$

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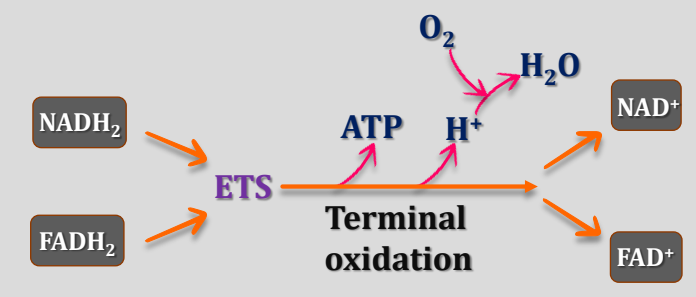
(C) Electron Transport System (ETS) or Respiratory Chain & Oxidative Phosphorylation :

i. All the reduced hydrogen acceptors like NADH + H^+ and $FADH_2$ move to the ETS where they release their hydrogen and get reoxidised to NAD^+ & FAD^+, so that they can again enter into the respiration process.

ii. ETS is the chain of some hydrogen and electron carriers present in the inner mitochondrial membrane.

iii. During this process hydrogen acceptors get reoxidised and ATP are produced.



Now components of ETS and ATP synthase are categorised as follows:

Name of complexes	Components of ETS
Complex I (NADH dehydrogenase complex)	FMN, Fe-S
Complex II (Succinic Dehydrogenase complex)	FAD, Fe-S
Complex III (Cytochrome C reductase complex)	Cyt b Cyt c_1, Fe-S
Complex IV (Cytochrome C oxidase complex)	Cyt. a and Cyt. a_3, 2Cu centers
Complex V (ATP Synthase/ ATPase/ Oxysome)	F_0 (Integral)- F_1(Peripheral)

Mechanism :

i. Electrons from NADH produced in the mitochondrial matrix during citric acid cycle are oxidised by an NADH dehydrogenase (complex I), and electrons are then transferred to ubiquinone located within the inner membrane.

ii. Ubiquinone also receives reducing equivalents via $FADH_2$ (complex II) that is generated during oxidation of succinate in the citric acid cycle.

iii. The reduced ubiquinone (ubiquinol) is then oxidised with the transfer of electrons to cytochrome c via cytochrome bc_1 complex (complex III).

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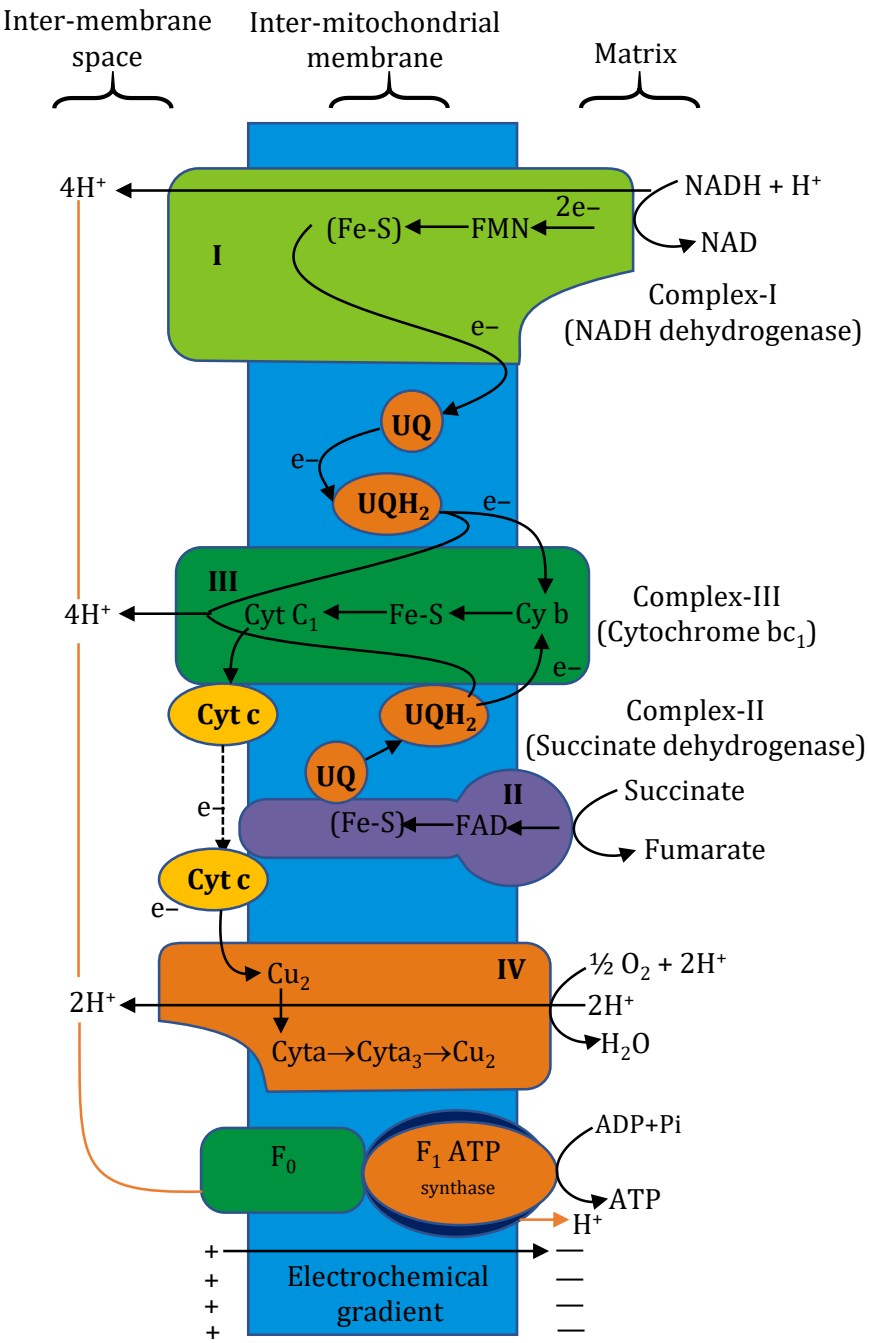

iv. Cytochrome c is a small protein attached to the outer surface of the inner membrane and acts as a mobile e^- carrier for transfer of electrons between complex III and IV.

v. Complex IV refers to cytochrome c oxidase complex containing cytochromes a and a_3, and two copper centres.

vi. When the electrons pass from one carrier to another via complex I to IV in the electron transport chain, they are coupled to ATP synthase (complex V) for the production of ATP from ADP and inorganic phosphate.

vii. The number of ATP molecules synthesised depends on the nature of the electron donor. Oxidation of one molecule of NADH gives rise to 3 molecules of ATP, while that of one molecule of $FADH_2$ produces 2 molecules of ATP.

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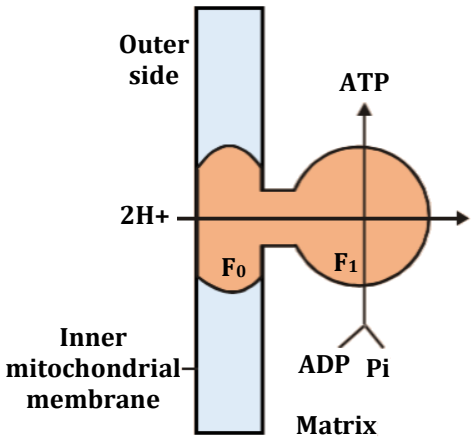
viii. Although the aerobic process of respiration takes place only in the presence of oxygen, the role of oxygen is limited to the terminal stage of the process. Yet, the presence of oxygen is vital, since it drives the whole process by removing hydrogen from the system. Oxygen acts as the final hydrogen acceptor.



- CoQ/UQ is a mobile $H(e^- + H^+)$ carrier and cyt-c is mobile e^- carrier. UQ is located within the inner mitochondrial membrane.
- O_2 is last H acceptor in oxidative phosphorylation & due to its reduction, water is formed.
- During each step of mitochondrial ETS, redox reaction occurs and energy is released which is utilized in creation of proton gradient for the synthesis of ATP in presence of oxygen (Oxidative phosphorylation).
- Passage of $2H^+$ through F_0 particle or proton channel leads to synthesis of 1 ATP.

Photophosphorylation	Oxidative phosphorylation
1. Occurs in chloroplast during photosynthesis	Occurs in mitochondria during respiration
2. Proton gradient develops across the thylakoid membrane	Proton gradient develops across the inner mitochondrial membrane
3. For ATP production the source of energy is light energy.	For ATP production the source of energy is oxidation

(D) Shuttle System:

- Cytosolic or extra mitochondrial or **glycolytic NADH** transported to ETS by **two type of shuttles** (Only in eukaryotes):
  (a) Glycerol phosphate shuttle $2NADH \longrightarrow 2FADH_2$
  (b) Malate aspartate shuttle $2NADH \longrightarrow 2NADH$
- In prokaryotes, shuttle mechanism is absent. They always get 38 ATP from aerobic respiration of 1 glucose.

6. The Respiratory Balance Sheet :

- Theoretical energy calculation for complete oxidation of one glucose molecule:

Step	Number of turn	ATP synthesis through substrate level phosphorylation	ATP gain through oxidative phosphorylation	ATP consumed	Net gain
EMP pathway	1	4	6 or 4	2	8 or 6
Link reaction	2	0	6	0	6
Kerbs cycle	2	2	22	0	24
Total	-	6	34 or 32	2	38 or 36

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- It is possible to make calculations of the **net gain of ATP** for every glucose molecule oxidised; but in reality, this can remain only a theoretical exercise. (These calculations can be made only on certain assumptions that) :-

(i) There is a sequential, orderly pathway functioning, with one substrate forming the next and with glycolysis, TCA cycle and ETS pathway following one after another.

(ii) The NADH synthesised in glycolysis is transferred into the mitochondria and undergoes oxidative phosphorylation.

(ii) None of the intermediates in the pathway are utilised to synthesise any other compound.

(iv) Only glucose is being respired–no other alternative substrates are entering in the pathway at any of the intermediary stages.

Note :- But this kind of assumptions are not really valid in a living system; all pathways work simultaneously and do not take place one after another; substrates enter the pathways and are withdrawn from it as and when necessary; ATP is utilised as and when needed; enzymatic rates are controlled by multiple means. Yet, it is useful to do this exercise to appreciate the beauty and efficiency of the living system in extraction and storing energy.

7. Respiration-Amphibolic Pathway :

i. Glucose is the favoured substrate for respiration. All carbohydrates are usually first converted into glucose before they are used for respiration. Other substrates can also be respired, as has been mentioned earlier, but then they do not enter the respiratory pathway at the first step.

ii. Fats would need to be broken down into glycerol and fatty acids first. If fatty acids were to be respired they would first be degraded to acetyl CoA and enter the pathway. Glycerol would enter the pathway after being converted to PGAL.

iii. The proteins would be degraded by proteases and the individual amino acids (after deamination) depending on their structure would enter the pathway at some stage within the Krebs' cycle or even as pyruvate or acetyl CoA.

iv. Since respiration involves breakdown of substrates, the respiratory process has traditionally been considered a catabolic process and the respiratory pathway as a catabolic pathway. But is this understanding correct? We have discussed above, at which points in the respiratory pathway different substrates would enter if they were to be respired and used to derive energy. What is important to recognise is that it is these very compounds that would be withdrawn from the respiratory pathway for the synthesis of the said substrates. Hence, fatty acids would be broken down to acetyl CoA before entering the respiratory pathway when it is used as a substrate. But when the organism needs to synthesise fatty acids, acetyl CoA would be withdrawn from the respiratory pathway for it. Hence, the respiratory pathway comes into the picture both during breakdown and synthesis of fatty acids. Similarly, during breakdown and synthesis of protein too, respiratory intermediates form the link. Breaking down processes within the living organism is catabolism, and synthesis is anabolism. Because the respiratory pathway is involved in both anabolism and catabolism, it would hence be better to consider the respiratory pathway as an amphibolic pathway rather than as a catabolic one.

Succinyl Co–A is important for the synthesis of porphyrin ring containing compounds like Chlorophylls, Phytochromes, Cytochromes, Haemoglobin etc.

α-ketoglutaric acid (5C) is involved in various amino acid formation.

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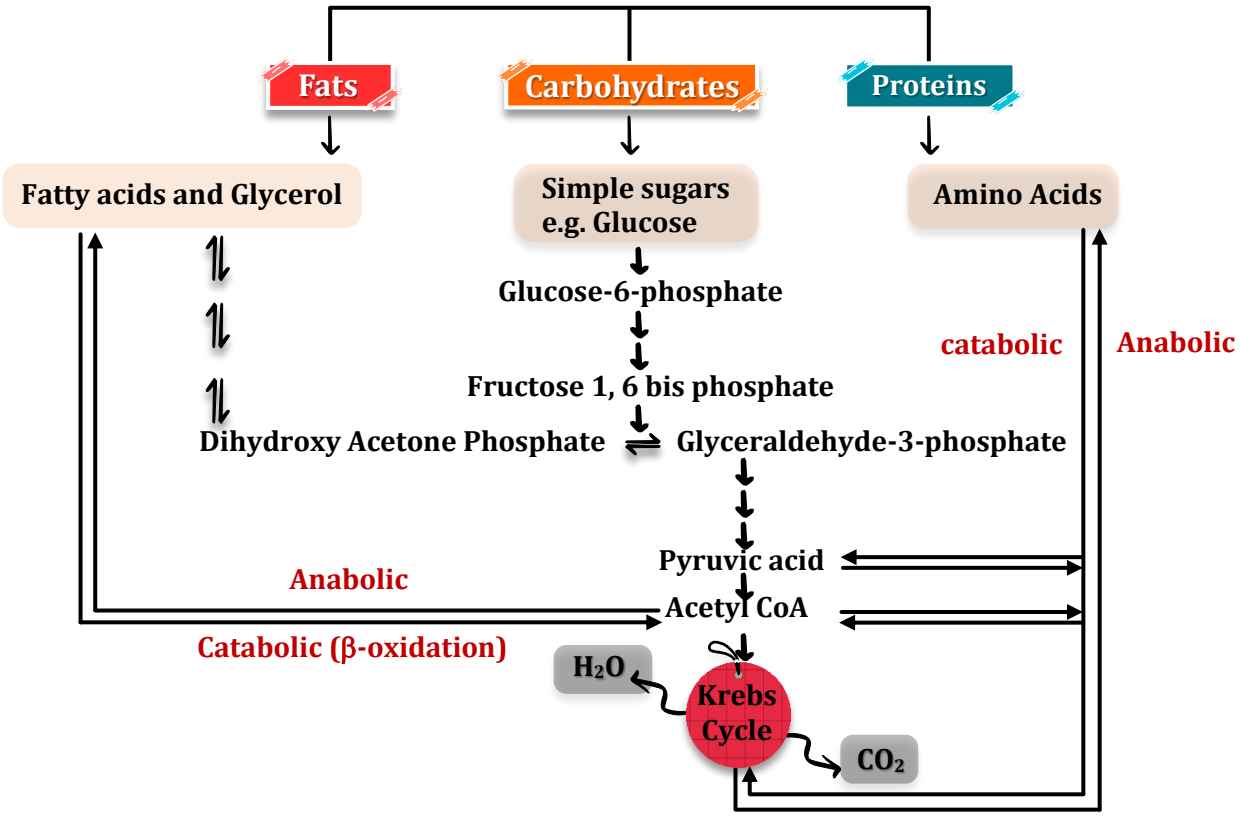

8. Respiratory Quotient (R.Q.) :

- The ratio of the volume of CO_2 evolved to the volume of O_2 consumed in respiration is called the respiratory quotient (RQ) or respiratory ratio.

$$RQ = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of } O_2 \text{ consumed}}$$

- The respiratory quotient depends upon the type of respiratory substrate used during respiration.

RQ = 1 **(Aerobic respiration)**

$$C_6H_{12}O_6 + 6O_2 + 6H_2O \longrightarrow 6CO_2 + 12H_2O + 686 \text{ Kcal kcal}$$

$$RQ = \frac{6\ CO_2}{6\ O_2} = 1.0$$

RQ = ∞ **(Anaerobic respiration)**

$$C_6H_{12}O_6 \longrightarrow 2CH_3CH_2OH + 2CO_2 + 59 \text{ kcal}$$

$$RQ = \frac{2\ CO_2}{\text{Zero } O_2} = \infty$$

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RQ = Zero

In succulent plants due to availability of insufficient O_2 glucose partially and RQ will be zero.

$$2C_6H_{12}O_6 + 3O_2 \rightarrow \underset{\text{Malic acid}}{3C_4H_6O_5} + 3H_2O + \text{Energy}$$

$$RQ = \frac{\text{Zero } CO_2}{3\ O_2} = 0$$

RQ = Less than one

- During complete oxidation of protein and fat
- During protoplasmic respiration (In case of a starved cell)
- In case of mixed diet
- In case of germinating fatty seeds.

$$2(C_{51}H_{98}O_6) + 145\ O_2 \rightarrow 102\ CO_2 + 98\ H_2O + \text{Energy}$$

Tripalmitin

$$RQ = \frac{102\ CO_2}{145\ O_2} = 0.7$$

When proteins are respiratory substrates the ratio would be about 0.8 or 0.9.

Pure proteins or fats are never used as respiratory substrates because before entering the respiratory pathway they must be converted into such compounds which can enter into the glycolysis or link reaction or Krebs cycle at their respective stages.

RQ = More than one

- During complete oxidation of organic acids.
- In case of maturing fatty seeds.

Oxalic acid

$$2(COOH)_2 + O_2 \rightarrow 4CO_2 + 2H_2O + \text{Energy}$$

RQ = 4.0

Malic acid

$$C_4H_6O_5 + 3O_2 \rightarrow 4CO_2 + 3H_2O + \text{Energy}$$

RQ = 1.33

Succinic acid

$$2C_4H_6O_4 + 7O_2 \rightarrow 8CO_2 + 6H_2O + \text{Energy}$$

RQ = 1.14

Energy efficiency of cellular respiration:

1 ATP = 8.1 Kcal

1 Glucose = 686 Kcal

If gain is 36 ATP then efficiency $= \frac{291.6}{686} \times 100 = 42.50\%$

If gain is 38 ATP then efficiency $= \frac{307.8}{686} \times 100 = 44.86\%$

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Golden Key Points

- **The significance of ETS is to remove hydrogens from reduced hydrogen acceptors NADH + H^+ & $FADH_2$. During this process hydrogen acceptors get reoxidised and ATP are produced.**
- Cytochrome c is a small protein attached to the outer surface of the inner membrane and acts as a mobile carrier for transfer of electrons between complex III and IV.
- Passage of $4H^+$ through F_0 particle or proton channel leads to synthesis of 1 ATP.
- Glucose is the favoured substrate for respiration.
- In both lactic acid and alcohol fermentation not much energy is released; less than seven percent of the energy in glucose is released.
- Yeasts poison themselves to death when the concentration of alcohol reaches about 13 percent.
- The respiratory quotient depends upon the type of respiratory substrate used during respiration.

BEGINNER'S BOX-2

AEROBIC RESPIRATION (ELECTRON TRANSPORT SYSTEM), THE RESPIRATORY BALANCE SHEET, RESPIRATION–AMPHIBOLIC PATHWAY, FERMENTATION, RESPIRATORY QUOTIENT (R.Q.)

1. How many molecules of ATP are produced per molecule of $FADH_2$ oxidised ?
(1) One (2) Two (3) Three (4) four

2. The value of RQ for carbohydrates is :-
(1) 1 (2) 2 (3) > 1 (4) Zero

3. By aerobic respiration of 1 molecule of PGAL how many ATP get synthesized ?
(1) 8 ATP (2) 2 ATP (3) 19 or 20 ATP (4) 36 ATP

4. Cytochromes are concerned with :-
(1) Protein synthesis (2) Cellular digestion
(3) Cell division (4) Cell-respiration

5. Number of oxygen molecules required for oxidation of $2NADH_2$ molecules in ETS ?
(1) 1 (2) 2 (3) 3 (4) 4

6. Electron and hydrogen carriers in ETS are located at -
(1) Outer membrane of mitochondria
(2) Inner membrane of mitochondria
(3) Mitochondrial matrix
(4) Intermembrane space

7. Which among the following is e^- and H^+ carrier?
(1) UQ (2) Cyt-C (3) FMN (4) Cyt-a_3

8. Final electron acceptor in oxidative phosphorylation is: -
(1) H_2O (2) O_2 (3) ATP (4) NADPH

9. Cyt- a_3 is present in which of the following complex?
(1) complex-I (2) complex-II (3) complex-III (4) complex-IV

10. Complex-II is also called as: -
(1) NADH dehydrogenase (2) Cytochrome C reductase
(3) Succinate dehydrogenase (4) Cytochrome c oxidase

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11. How many ATPs are formed during glycolysis through substrate level photophosphorylation?
(1) Three (2) Four (3) Five (4) Six

12. Total number of ATPs formed due to Krebs cycle are -
(1) 22 (2) 24 (3) 26 (4) 28

13. The ratio of the volume of CO_2 evolved to the volume of O_2 consumed in respiration is called as -
(1) CO_2 compensation point (2) O_2 compensation point
(3) Respiratory quotient (4) Transpiration ratio

14. Which among the following can acts as respiratory substrates?
(1) Carbohydrates (2) Fats
(3) Proteins (4) All of the above

15. RQ of the carbohydrates can be -
(1) One (2) Infinite (3) Zero (4) All of the above

BEGINNER'S BOX ANSWERS KEY

BEGINNER'S BOX-1	Que.	1	2	3	4	5	6	7	8	9	10
	Ans.	2	3	2	4	4	4	3	2	3	4
	Que.	11	12	13	14	15	16	17	18	19	20
	Ans.	4	3	4	4	3	3	3	1	4	2

BEGINNER'S BOX-2	Que.	1	2	3	4	5	6	7	8	9	10
	Ans.	2	1	3	4	1	2	1	2	4	3
	Que.	11	12	13	14	15					
	Ans.	2	2	3	4	4					

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ESSENCE

Glycolysis :
- In Cytoplasm
- Common in both aerobic and anaerobic organisms

Glucose (6C)
$C_6H_{12}O_6$

2ATP → 2NADH+H⁺ → MAS → 6ATP
2ATP → 2NADH+H⁺ → GPS → 4ATP
2ATP → 4ATP

2X Pyruvic Acid (3C)
$C_3H_4O_3$

MAS = Malate Aspartate Shuttle
GPS = Glycerol Phosphate Shuttle

In Anaerobic conditions

Anaerobic Respiration or Fermentation

2X Pyruvic Acid (3C)
$C_3H_4O_3$

- 2X Ethyl Alcohol + $2CO_2$ (C_2H_5OH)
- 2X Lactic Acid ($C_3H_6O_3$)

or

In Aerobic conditions

2X Pyruvic Acid (3C)
$C_3H_4O_3$

Link Reaction :
- In Matrix of mitochondria
- Link between Glycolysis and Krebs Cycle

NADH + H⁺, CO_2 ← Acetyl Co-A (2C) → NADH + H⁺, CO_2

Acetyl Co-A (2C) → OAA (4C) → Citric Acid (6C)
OAA (4C) → NADH+H⁺
Citric Acid (6C) → NADH+H⁺, CO_2
Fumaric Acid (4C) → $FADH_2$
Succinic Acid (4C) → GTP, CO_2, NADH+H⁺ → α- Ketoglutaric acid (5C)

Acetyl Co-A (2C) → OAA (4C) → Citric Acid (6C)
OAA (4C) → NADH+H⁺
Citric Acid (6C) → NADH+H⁺, CO_2
Fumaric Acid (4C) → $FADH_2$
Succinic Acid (4C) → GTP, CO_2, NADH+H⁺ → α- Ketoglutaric acid (5C)

ETS (Electron transport system) Oxidative Phosphorylation

- In inner membrane of mitochondria
- 1 NADH+H⁺ = 3 ATP
- 1 $FADH_2$ = 2 ATP

Step	Number of turn	ATP synthesis through substrate level phosphorylation	ATP gain through oxidative phosphorylation	ATP consumed	Net gain
EMP pathway	1	4	6 or 4	2	8 or 6
Link reaction	2	0	6	0	6
Krebs cycle	2	2	22	0	24

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